Neutrino Shortcuts in Spacetime

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Abstract

Theories with large extra dimensions may be tested using sterile neutrinos living in the bulk. A bulk neutrino can mix with a flavor neutrino localized in the brane leading to unconventional patterns of neutrino oscillations. A resonance phenomenon, strong mixing between the flavor and the sterile neutrino, allows to determine the radius of the large extra dimension. If our brane is curved, then the sterile neutrino can take a shortcut through the bulk, leading to an apparent superluminal neutrino speed. The amount of "superluminality" is directly connected to parameters determining the shape of the brane. On the experimental side, we suggest that a long baseline neutrino beam from CERN to NESTOR neutrino telescope will help to clarify these important issues.

The standard model of strong and electroweak interactions has been extremely successful. Still we know that it cannot be regarded as the final theory. Any attempt to include gravity leads to a unified theory where two disparate scales coexists: the electroweak scale ($M_W \sim 1\,TeV$) and the Planck scale ($M_{Pl} \sim 10^{19}\,GeV$), with an "energy desert" extended between them. Quantum corrections tend to mix the scales and an incredible amount of fine-tuning is required (the hierarchy problem).

A novel approach has been suggested by replacing the "energy desert" with an extra dimensional space [1-4]. Our four-dimensional world is embedded in a higher dimensional space with D dimensions ($D = 4 + n$). While the standard model fields are constrained to live on the 4-dimensional brane, gravitons

and standard model singlets, like a sterile neutrino, can freely propagate in the higher-dimensional space (bulk). The fundamental scale M_f of gravity in D-dimensions is related to the observed 4-dimensional Planck scale M_{Pl} by

$$M_{Pl}^2 = M_f^{2+n} V_n \tag{1}$$

where V_n is the volume of the extra space. For a torus configuration

$$V_n = (2\pi)^n R_1 R_2 \cdots R_n \tag{2}$$

with R_i $(i = 1, 2, \cdots, n)$ the radii of extra dimensions. Then for a sufficiently large volume V_n the fundamental scale of gravity M_f can be as low as M_W. In this radical way the hierarchy problem ceases to exist as such. A phenomenology of TeV gravity has been undertaken already [5, 6].

Neutrinos, from the time of their inception, some 80 years ago, remain enigmatic and elucive. Their masses, their couplings to other particles, the number of their flavors or types, the transformations among themselves, remain relatively unknown. The diverse range of the neutrino parameters allow them to play an important role from the universe evolution, galaxy dynamics, energy generation within stars, to subatomic physics and fundamental symmetries shaping the interactions of the elementary particles. A sterile neutrino propagating in the bulk, may provide informations on the extra dimensions and on properties of the brane we are living in. It is the purpose of this letter to examine and analyze this type of information.

A sterile neutrino propagating in the compact extra dimensions will appear at the 4-dimensional brane as a Kaluza - Klein (KK) tower of states, i.e. an infinite number of 4-dimensional spinors.The Yukawa coupling of the standard left-handed lepton doublet, the Higgs scalar and the right-handed bulk neutrino will provide a mixing between the left-handed neutrino of the standard model and the KK modes. Compared to the usual oscillations, novel features appear since now we have a coupled system of infinite degrees of freedom. An extensive literature on sterile neutrinos living in extra dimensions, highlights the important aspects of an underlying rich dynamics [7-19].

For simplicity we consider a single flavor neutrino, the muon neutrino, and a single large extra dimenion of radius R. We assume all other dimensions are smaller and do not affect our analysis. A strong mixing between the muon neutrino and the sterile KK states is observed, whenever a resonance condition is satisfied, an equality between the effective mass of ν_μ within matter and the mass parameters of the KK states [19]

$$\frac{G_F\, \varrho\, E_\nu}{\sqrt{2} M_N} = \frac{n^2}{R^2} \tag{3}$$

Here M_N is the nucleon mass, E_ν is the neutrino energy, ϱ is the density of the medium traversed and n is referring to the nth KK state (n=1, 2, 3, ...). The most significant transition occurs for $n = 1$ and the relationship (3) takes the form

$$\left(\frac{\varrho}{10\,gr/cm^3}\right)\left(\frac{E_\nu}{100\,GeV}\right)\left(\frac{R}{1\,\mu m}\right)^2 \simeq 1 \tag{4}$$

The above condition guarantees that the transition of the muon neutrino to the sterile neutrino and inversely, occurs with a sizeable probability. If such a resonance phenomenon is observed, we may extract the radius of the extra dimension. For example, for CERN neutrinos with $E_\nu = 30\,GeV$ and an average density ϱ of $5\,gr/cm^3$, relation (4) implies a radius R of the extra dimension close to few μm.

Measurements of the neutrino time travel have been presented by MINOS and OPERA experiments [20, 21]. There the possibility of neutrinos "running faster than light" has been entertained. A number of theoretical proposals have been advanced involving newphysics, or violations of the Lorentz symmetry [22-32]. In our work we address the issue of the "superluminal" neutrinos within the theories of large extra dimensions, suggesting that the sterile neutrino takes a "shortcut" through the bulk. Our brane we are living in, rather than a flat brane, may be a curved brane. On general grounds in a brane containing matter and energy, self-gravity will induce a curvature to the brane, so that the brane becomes concave towards the bulk in the null direction. Then we can find geodesics in the bulk propagating signals faster compared to the geodesics in the brane [33]. Standard-model neutrinos ν_e, ν_μ, ν_τ are stuck in the brane. A sterile neutrino though may leave a point on the brane and emerge to another point on the brane, by taking the "shortcut" through the bulk and arriving earlier compared to a flavor neutrino which follows a geodesic on the brane. A two dimensional toy model may exhibit the expected behavior [34, 35, 36]. In a Minkowski metric

$$ds^2 = dt^2 - dx_1^2 - dx_2^2 \tag{5}$$

the curved brane is represented by

$$x_2 = A sin\, kx_1 \tag{6}$$

while the bulk geodesic is given by $x_2 = 0$. A sterile neutrino propagating through the bulk will appear as having a superluminal speed. The time difference between the two geodesics is given by

$$\frac{t_b - t_s}{t_b} \simeq \left(\frac{Ak}{2}\right)^2 \tag{7}$$

where t_b (t_s) is the travel time of the flavor (sterile) neutrino. Denoting by v the effective speed of the sterile neutrino and c the speed of light, eqn. (7) takes the form

$$\frac{v-c}{c} = \left(\frac{Ak}{2}\right)^2 . \tag{8}$$

Thus an experimental measurement of a time difference will provide information on the geometry of our brane, notably the brane shape parameter Ak.

Within the theories of large extra dimensions, neutrinos appear as the ideal mediators to convey information about the geometry of the bulk and the shape of the brane. We considered the oscillation between a flavor neutrino living in the brane and a sterile neutrino circulating in the bulk. Our study indicates that this type of neutrino oscillations may reveal features of the overall geometry. Further experiments are needed to elucidate these important aspects. We suggest that a neutrino beam from CERN directed to the NESTOR neutrino telescope, of the coast of Pylos, will help in this direction [37]. The large CERN-NESTOR distance (1676 km), the different neutrino detection techniques, offer additional leverage to study a crucial issue.

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